

Spatial patterns of infection: The 2001 Foot-and-Mouth Epidemic in Uruguay

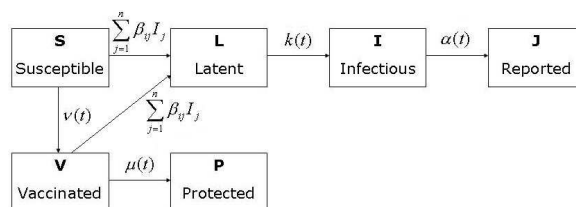
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Foot-and-Mouth disease (FMD) is a highly infectious illness of livestock and a serious economic threat. In 2001, there were major outbreaks of FMD in Great Britain and Uruguay. In Great Britain, at least 4 million animals were destroyed during the epidemic and the exportation of animal goods was not permitted for over 6 months after the epidemic.

We model the 2001 FMD epidemic in Uruguay using an explicit discrete spatial epidemic model that includes geo-referenced data (Figure 1). Susceptible farms in county i become infected at rate $\sum_{j=1}^n \beta_{ij} I_j$ ($i = 1, 2, \dots, n$) where β is the transmission rate and I_j is the number of infectious farms in county j . The rate of infection is assumed to be directly proportional to the additive effects from all infected farms in all counties. Latent farms progress to the infectious state after a mean time of $1/k$ days and the infectious farms are detected at rate α . Movement restrictions (starting on 27 April 2001) are modeled as a reduction in the mean transmission rate within counties. Once the mass vaccination program started (05 May 2001), susceptible farms (S) were vaccinated at rate v . Vaccinated farms (V) become protected (P) at rate μ .

We use the inter-county distances (i.e. Euclidean distances between county centroids) as a measure of the connectivity between counties. The number of FMD cases reported in each county was obtained from geo-referenced case reports. We grouped the 19 Uruguayan states into three contiguous regions (Region I, II and III) in the map of Uruguay (Figure 2).

The spatially explicit model for the develop-



Schematic representation of the state progression of farms in a given county.

ment and testing of FMD control measures was compared with a simple spatially homogeneous model. Spatially homogeneous models are limited by their inability to capture the spatial spread of the epidemic. Our discrete spatial model captures a double peak observed in the incidence of new cases in the Uruguayan epidemic. This pattern was not observed in the spatially homogeneous model (Figure 3).

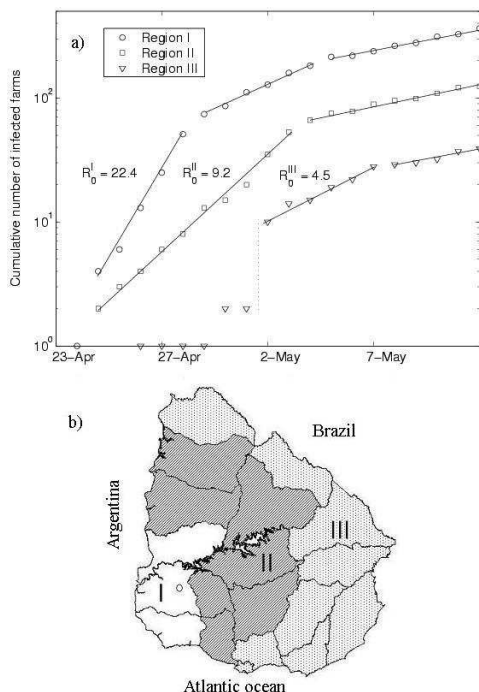
We defined internal (within counties) and external (across counties) reproductive numbers, that is, within and across-county contributions to the average number of secondary infections under low levels of local infection. We estimate a mean internal basic reproductive number $\bar{R}_0^{in} \approx 280.47$ while the external $\bar{R}_0^{out} \approx 2.64$. Movement restrictions reduced them to $\bar{R}_m^{in} \approx 87$ and $\bar{R}_m^{out} \approx 0.82$. Twelve days after the start of the mass vaccination policy the internal reproductive number dropped to less than one. Our model predicts that if the mass vaccination program had been delayed an additional five days, then there would have been 50% more cases. If the vaccination program had been implemented 5 days prior to the actual date, our model predicts the epidemic would have been reduced by 37%.

Conclusions

FMD epidemic models with spatial structure can capture regional patterns of spread.

Long distance sparks of infection reaching areas of susceptible farms can generate multiple peaks in the global infection rates. In contrast to spatially structured models, spatially homogeneous models are unable to reproduce such

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a) The initial intrinsic growth rate r in Region I, II and III are 0.65, 0.35, and 0.19 respectively ; b) Region I, II and III comprise 3, 7 and 8 Uruguayan states respectively. We estimate the intrinsic growth rate in region III using the cumulative number of cases from 02 May to 07 May 2001 due to underreporting of number of cases before 02 May 2001. The intrinsic growth rate after 07 May 2001 is approximately the same in the three regions once movement restrictions and some depletion in the number of susceptible farms had taken place.

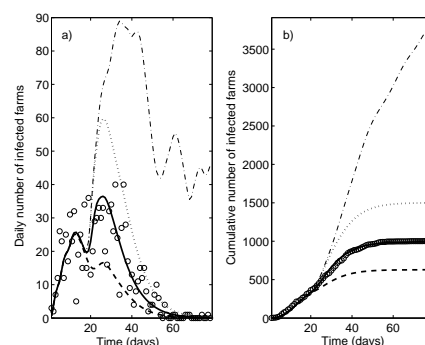
patterns of infection.

Our model predicts the basic reproductive number rapidly decreases after movement restrictions are imposed. This observation agrees with the rapid decrease in the intrinsic growth rate observed in the incidence data for each of the Uruguayan regions.

There was a rapid drop in the external reproductive number to less than one after movement restrictions were enforced. Following these

restrictions, transmissions were localized and there was a very low probability for long-range transmission events. Hence, ensuring that movement restrictions are strictly enforced is crucial in any contingency plan against FMD.

The 2001 FMD Uruguayan epidemic data and analysis can be used for comparison when assessing other control measures such as culling policies and higher potency vaccines implemented alone or in combination with other interventions.



a) The daily and b) cumulative number of reported infected farms in Region I where the outbreak started (23 April 2001) and focused (57% of cases). Movement restrictions were implemented on 27 April 2001 and mass vaccination started on 05 May 2001. Circles are the data and the solid line is the model. Three scenarios are shown: (dash-dot) no mass vaccination implemented after movement restrictions (total of 5252 cases); (dot-dot) mass vaccination with a 5-day delay (1551 cases) and (dash-dash) 5 days before the actual date at which mass vaccination started (604 cases).

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